ELSEVIER

Journal of Hydrology 188–189 (1997) 946–964

Journal of Hydrology

A daily resolution evapoclimatonomy model applied to surface water balance calculations at the HAPEX-Sahel supersites

Sharon E. Nicholson[a,*], José A. Marengo[a], Jeeyoung Kim[a], Andrew R. Lare[b], Sylvie Galle[c], Yann H. Kerr[d]

[a]*Department of Meteorology, Florida State University, Tallahassee, FL 32306, USA*
[b]*Applied Research Corporation, NASA/GSFC-Code 913, Greenbelt, MD 20771, USA*
[c]*ORSTOM, Laboratorie D'Hydrologie, Montpellier, France*
[d]*Laboratoire d'Etude et de Recherche en Télédétection Spatiale (LERTS), Toulouse, France*

Abstract

This paper describes the results of Lettau's evapoclimatonomy model at daily time scales as applied to the Central East and Southern supersites of the HAPEX-Sahel region in Niger, West Africa. A revised version of the evapoclimatonomy model has been applied to the millet and bush fallow (*Guiera senegalensis*) fields at both supersites during the intensive observation period (IOP; 20 August–12 October, 1992), using daily means of precipitation, potential evapotranspiration, solar radiation, normalized difference vegetation index (NDVI) from the HAPEX-Sahel observations, as well as vegetation and soil parameters for the region. Soil moisture and immediate and delayed evapotranspiration and runoff are predicted. It has been found that the model predicts the soil moisture at the Central Eastern supersite quite well. However, it overestimates soil moisture at the Southern supersite even though its variability is captured by the model. Model results also indicate that soil moisture estimates are very sensitive to the NDVI–evaporivity relationship, which is robust at monthly scales but needs more revision for application at the daily scale. Overall the model performance when applied to the IOP observations is sufficiently good to indicate the suitability of the climatonomy for water balance studies on daily time scales.

1. Introduction

There is increasing evidence that land surface processes are involved in the development and maintenance of severe and prolonged continental droughts (Entekhabi

* Corresponding author.

PII S0022-1694(96)03178-2

et al., 1992; Brubaker et al., 1993). This seems to be particularly true of the West African Sahel (Nicholson, 1986, 1989). Thus the numerical simulation of Sahel climate requires an appropriate treatment of land surface processes (e.g. Xue and Shukla, 1993).

We have developed a comprehensive surface energy and water balance model (e.g. Lare and Nicholson, 1994; Nicholson et al., 1996) for use in our Sahel climate studies. It is a revision of a model which Lettau developed and termed "climatonomy" to denote its quantitative approach to climate studies (e.g. Lettau, 1969; Lettau and Baradas, 1973). This model has proved useful in deriving water balance on monthly time scales in West Africa (Marengo et al., 1996). Neither the original model nor our revised version have been applied on daily time scales. Simulation on the daily scale is particularly important in a semi-arid subtropical region, where the time scales associated with hydrological processes are on the order of days.

The goal of this work is to reformulate the evapoclimatonomy subunit of the model for use on daily time scales and to test its application on both shorter time scales and smaller space scales. The time and space scales of the HAPEX-Sahel experiment in Niger, West Africa, afford an excellent opportunity to test the model at higher temporal and spatial resolution. The three 'supersites' of the experiment (Goutorbe et al., 1994; Prince et al., 1994) provide a variety of typical Sahelian conditions and they reflect the north–south gradient of soil moisture, rainfall, and vegetation dynamics (Kabat et al., 1993), which is so typical of the region.

In this paper, we describe the basic changes in the model and apply it to the HAPEX-Sahel region of West Africa, utilizing data from the experiment. Soil moisture, evapotranspiration and runoff are calculated for the intensive observational period (IOP) from August to October 1992. The model is forced with initial conditions derived from HAPEX-Sahel observations, as well as soil characteristics and satellite-derived indices of vegetation for all three supersites. The data collected during the IOP cover a wide range of meteorological and hydrological conditions seen in the region and are therefore very appropriate for testing the evapoclimatonomy model.

2. The evapoclimatonomy model

2.1. Model overview

The evapoclimatonomy model is essentially a numerical solution to the hydrologic balance equation:

$$P = N + E + \mathrm{d}m/\mathrm{d}t \tag{1}$$

where P is precipitation, N is runoff, E is evapotranspiration, and $\mathrm{d}m/\mathrm{d}t$ denotes changes in soil moisture storage m. The model is forced by ground-absorbed solar radiation and rainfall; output consists of areally averaged soil moisture, evapotranspiration and runoff (Fig. 1). Input variables, in addition to forcing functions, include surface and vegetation characteristics. The model includes two soil layers: a surface layer from 0 to 0.10 m and a bulk layer (inclusive of the surface layer) from 0 to 1.00 m. The surface layer determines the surface (immediate) runoff, while the bulk layer controls gravitational drainage. It is

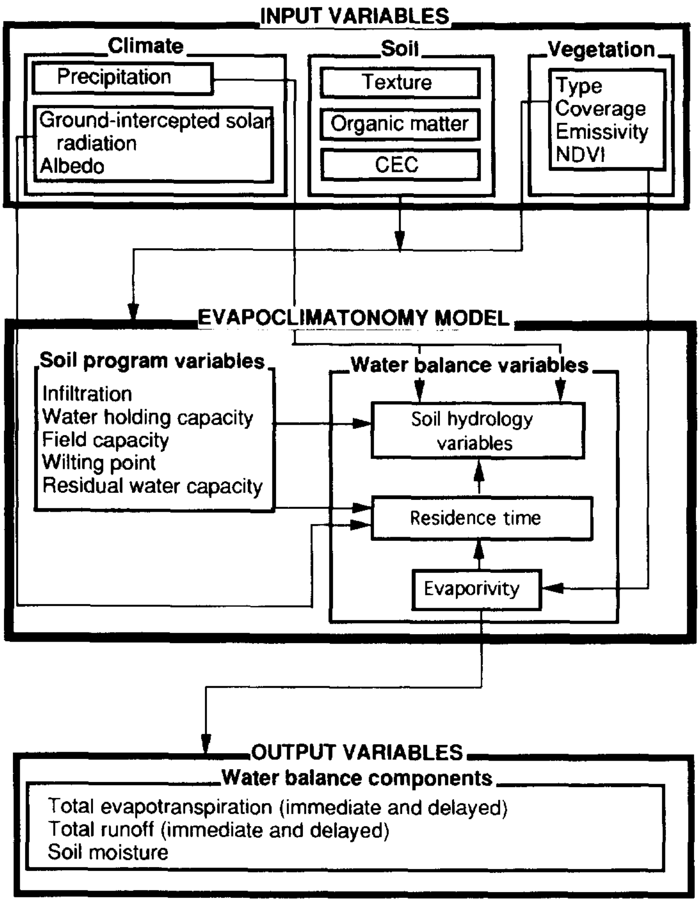

Fig. 1. Schematic of the evapoclimatonomy model.

assumed that soil moisture exchange processes on the time scale of the model are confined to the 1.00-m layer.

Two other assumptions are made to keep the model simple (Lare and Nicholson, 1990). The first is that runoff and evapotranspiration can be subdivided into immediate and delayed components, respectively constituting processes that occur in the same month as the precipitation and those associated with rain that fell in previous months. Physically this separates temporal variations of runoff and evapotranspiration associated with superficial water from those utilizing subsurface moisture (Nicholson and Lare, 1990). Second, the delayed processes are assumed to be proportional to soil moisture content. Details of the model are found in Lare and Nicholson (1994) and Nicholson et al. (1996); some of the more important concepts are summarized below.

An important model parameter is 'residence time' t^*, a concept introduced to facilitate the solution of the model equation by creating a non-dimensional time scale. It is calculated after Serafini and Sud (1987) as a function of potential evapotranspiration

(PET), the wilting point Wp (the point at which the vegetation cannot absorb enough moisture to sustain itself and begins to wilt), and the water holding capacity of the soil Wfc

$$t^* = \frac{1 - e^{\alpha_v}}{\frac{\alpha_v}{Wfc - Wp}\mathrm{PET}} \ln\left[\frac{e^{Wfc} - 1}{e^{Wp} - 1}\right]\left[\frac{Wfc - rwc}{Wfc - Wp}\right] \tag{2}$$

where α_v accounts for variations in vegetation type and is set at 6.81 for this region (Mintz and Serafini, 1984). The parameter t^* represents the time required for a volume of water equal to the annual mean of exchangeable soil moisture to be depleted by the delayed processes of runoff and evapotranspiration. PET for the IOP was obtained from the HAPEX-Sahel Information System; otherwise, from FAO (1984).

A second parameter, termed 'evaporivity' e^*, is empirically estimated. Evaporivity is essentially a non-linear measure of the efficiency at which the land surface utilizes monthly solar radiation to evaporate precipitation received in the same month (Lare, 1992). It represents the portion of the incoming solar radiation that is utilized for evapotranspiration and is thus analogous to potential evapotranspiration. Its calculation is based on the normalized difference vegetation index (NDVI) (Nicholson et al., 1996).

Model runoff is generated by gravitational drainage of soil water (a 'delayed' process) and surface runoff (an 'immediate' process) due to precipitation exceeding infiltration rate (Warrilow, 1986). Gravitational drainage is a function of soil texture and moisture content; infiltration rate is a function of soil texture.

Infiltration is allowed to vary according to soil type, vegetation density and structure, as well as ground cover. It is a function of hydraulic conductivity, which in turn is a function of soil moisture and texture. Infiltration rates decrease rapidly during the early part of a storm, becoming nearly constant after about 30 min to 1 h, depending on the surface conditions and soil structure. For large rainstorms, it is primarily the final rate that determines the amount of surface runoff produced.

If the immediate top surface of the soil is saturated by rainfall, the infiltration for bare soil is calculated following Saxton et al. (1986). The effective hydraulic conductivity includes the bare soil infiltration, as well as the presence of vegetation canopy, ground cover, and surface rocks, as proposed by Rawls and Baumer (1989). A residual water capacity and a crusting parameter are also calculated (Rawls and Baumer, 1989, and Brakensieck and Rawls, 1983, respectively). Details of these parameterizations are presented in Lare and Nicholson (1994) and Nicholson et al. (1996).

The evapoclimatonomy model has been applied to a variety of climatic problems in select regions of Africa (e.g. Nicholson and Lare, 1990; Farrar et al., 1994; Nicholson et al., 1996). Excellent agreement between model calculated soil moisture and NDVI in diverse situations suggests the validity and robustness of its application. Sensitivity studies with the model were carried out by Nicholson and Lare (1990).

2.2. Revisions for daily scale

To adapt the model for daily time scales, revisions are required in the immediate runoff and evapotranspiration parameters. Following Lare (1992), evaporivity e^* can be expressed by the semi-empirical formula

$$e^* = 1/(1.25 + 6.25\ \mathrm{NDVI}) \tag{3}$$

and immediate evapotranspiration.

Immediate runoff E' is calculated as

$$E' = e^*(P - N')Rs/Rs_{\mathrm{avg}} \tag{4}$$

where P is precipitation rate, N' is the immediate runoff, Rs and Rs_{avg} are the daily and the IOP averaged ground absorbed solar radiation, respectively, which depend on global incident solar radiation and the surface albedo. E' was constrained not exceed PET.

Immediate runoff N' can be expressed as

$$N' = P \exp(-aF/P) \tag{5}$$

where F is infiltration rate and a is a proportionality constant (Warrilow, 1986). N' is set to be zero if there is no precipitation or if the infiltration rate exceeds precipitation. In the Warrilow (1986) formulation, the proportionality constant represents a particular fraction of a grid box over which rain would typically occur. On the small space scales on which we are applying this model, a is set equal to 1.

To accurately model surface runoff on daily scales, the time step involved should be on the order of minutes or hours instead of the monthly times scales in Lare and Nicholson (1994) and Marengo et al. (1996). To increase the model resolution, an analysis of daily rainfall and storm duration from hourly surface observations at Niamey Airport was performed, similar to the Lare (1992) calculations at monthly scales. The analysis was conducted using data from contrasting extreme wet and dry years. Taking the storm duration into account, Eq. (5) was modified as follows:

$$N' = P_{\mathrm{h}} t_{\mathrm{d}} \exp(-aF/P_{\mathrm{h}}) \tag{6}$$

where P_{h} is the mean daily rainfall rate in mm h^{-1}, t_{d} is the mean daily total storm duration in h day^{-1}, and F is the infiltration rate (see Section 2.1, also Lare, 1992; Lare and Nicholson, 1994). Following Warrilow (1986), immediate runoff is set to zero when this P_{h} is smaller that 4 mm h^{-1} for coarse-textured soils. The total storm duration for any month as a function of the daily rainfall is found to be

$$t_{\mathrm{d}} = 0.756\ P^{0.43718} \tag{7}$$

The daily hourly rainfall rate P_{h} as a function of daily rainfall P is then expressed as

$$P_{\mathrm{h}} = 1.3226\ P^{0.56282} \tag{8}$$

This formulation would be valid for most of Sahelian West Africa.

3. Background and data

3.1. Supersites and vegetation

The experiment was set within a 100-km square (2°–3°E, 13°–14°N) in Niger, West Africa (Goutorbe et al., 1994). Within this area measurements were carried out mainly in three supersites: Southern, Central West, and Central East. The size of the supersites (200–400 km^2) matches the scale at which the atmospheric boundary layer responds to changes in the land surface. Within these supersites were intensively monitored subsites representing the regions main crop, millet, and the principal natural vegetation types: tiger bush, fallow grass, and bush fallow (*Guiera senegalensis*). The Southern and Central West sites were intended primarily for surface flux and energy balance studies while the Central East site was selected primarily as a catchment for hydrologic studies (Prince et al., 1994).

3.2. HAPEX-Sahel observations used in this study

The HAPEX-Sahel experiment included a strong hydrological component. An important issue was how best to assign a mean (large-scale) value to spatially heterogeneous processes such as runoff. Since the evapoclimatonomy model produces representative spatial averages, we used observations from HAPEX-Sahel to run the model and examined the relationships between modeled and observed hydrological variables. The data were collected at a time of the year when vegetation and soil moisture change rapidly in response to meteorological conditions, radically transforming the surface energy balance. The HAPEX-Sahel data used were obtained from the HAPEX-Sahel Information System; these are indicated in Table 1.

3.2.1. Climatological data

Rainfall was measured by the EPSAT-Niger network of 100 recording raingauges for the three supersites (Lebel et al., 1992). The first data from EPSAT-Niger have shown that the spatial variability of rainfall is very large on all time scales (Lebel et al., 1995a, b; Lebel and LeBarbe, 1997). As in Marengo et al. (1996), rainfall was averaged at the local field scale, which is more representative than average rainfall for the entire supersite. The

Table 1

Observations from the HAPEX-Sahel Information System used in this study. The name of the file and supersite (CE, SS) and a description and particular data set are indicated. The specific data sets used are indicated in parenthesis in the second column

Data set name	Description	Supersite
EPSAT_DAILY_RAINFALL_92	Daily rainfall from ESPAT network (average rainfall for stations and sites)	CE, SS
CLIMAT_92_DAILY_DAT	Climatic data from 1992 (solar radiation)	CE
RAD_READING_DAT	Radiation data from University of Reading, UK (incident and reflected solar radiation at surface)	SS
SOIL_WATER_PROF_DAT	Soil water profile data (volumetric soil moisture measurements from 5 cm to 2.4 m)	SS
AVHRR_92_EXTRACT	Satellite estimates of radiances and fluxes (NDVI data)	CE, SS
NEUTRON_PROB_DAT	Volumetric moisture content from neutron probes (volumetric soil moisture measurements from 5 cm to 2.5 m)	SS, CE
CO_CLIMAT_DAT	Climatic and fluxes data (incident and reflected solar radiation at surface, latent heat)	CW
CLIMAT_92_DAILY	Climatic hourly data for 1992 (PET, solar radiation)	CE

largest spatial gradient in rainfall was observed over the Southern supersite, while over the Central East and West supersites rainfall distribution was more homogeneous. Rainfall data from the three supersites were kindly provided by T. Lebel (ORSTOM, France) and the EPSAT-Niger team.

Daily climatological quantities and fluxes were obtained primarily for the Central East supersite, and were provided by B. Monteny (ORSTOM, France). Hydrological measurements and heat fluxes over both bare soils and vegetated surfaces were measured for each of the major land-use types at each supersite, using micrometeorological techniques to give averages at the field scale (Monteny, 1993). These observations include global radiation at the surface, standard evaporation, potential evapotranspiration, maximum and minimum temperature, and wind speed, and are used mainly to provide a set of initial conditions for the evapoclimatonomy model runs.

3.2.2. Soil moisture

Extensive networks were set up for monitoring soil moisture primarily for the Central East and Southern supersites. Volumetric water content measurements were made for tiger bush and millet at the Central East supersite and for bush fallow, millet, and tiger bush for the Southern site. For the purposes of this work, we will not include tiger bush in our analysis. Soil moisture measurements were made at intervals of 1–7 days at given depths and transects, and were provided by J.D. Cooper (Institute of Hydrology, UK), and S. Galle (ORSTOM, France). Soil moisture was measured using neutron probes (Gardner et al., 1991). Measurements from all observation layers from the surface to 1.00 m were integrated to compare with soil moisture estimated by the evapoclimatonomy model. To validate our model, we used the average measurements of between seven to ten probes at each site.

3.2.3. Vegetation and remotely sensed data

Remotely sensed data were used to estimate surface albedo and the normalized difference vegetation index (NDVI) (Tucker et al., 1981, 1983, 1985; Tucker and Sellers, 1986) using NOAA AVHRR high resolution picture transmission data (1 × 1 km) after geometric and radiometric corrections. A 512 × 512 km area centered on the 1° × 1°square of the HAPEX-Sahel measurements was used (Kerr et al., 1992, 1993). AVHRR data were processed by Y. Kerr (LERTS-CESBIO, France) and details can be found in the documentation file of the CD-ROM (Kerr et al., 1993).

Daily albedo was estimated from the measurements of incident and reflected solar radiation for both the Central East and Southern supersites (Table 1). Other vegetation parameters, assumed as constant during the IOP, are the upper and lower story vegetation cover from Dorman and Sellers (1989).

3.3. Soil characteristics

For the HAPEX-Sahel grid box, soil type is generally luvic arenosols (FAO/UNESCO, 1977; Zobler, 1986). The textures associated with these soils in the Sahel are sand and clay contents of 93.0% and 5.7%, respectively, for the surface layer and 88.6% and 8.4% for the 1-m bulk layer (Webb et al., 1991). These are nearly identical to textural values given by

Wallace et al. (1994) for the bush fallow and millet sites at the Southern supersite and by B. Monteny (personal communication, 1995) for soils in the millet site at the Central East supersite. Organic matter is assumed to be 0.30% for the entire soil profile in both supersites. Additional soil information for model input was derived from FAO/UNESCO (1977) and from Zobler (1986). The latter source has soil information for a $1° \times 1°$ grid, which is comparable with the HAPEX-Sahel $1° \times 1°$ domain.

4. Methodology

4.1. Model implementation

This study used the evapoclimatonomy subunit of the climatonomy model, with revisions as described in Section 2. Although the shortwave subunit was also developed (Lare and Nicholson, 1990), it was not utilized here because the input data it produces for the evapoclimatonomy model were available from localized HAPEX-Sahel measurements. The model was run on the daily time scale for fields in all three supersites for 1 year, to properly spin up the model to the climatic mean state. As the integration is non-linear, perfect equilibrium between precipitation, evapotranspiration, runoff and changes in soil moisture storage are not to be expected; however, in this respect the model gave errors of less than 2%.

In the model, changes in soil moisture are computed from the rates of rainfall, immediate evapotranspiration, and immediate runoff. If computed soil moisture exceeds field capacity, the excess moisture is removed as delayed runoff. When evapotranspiration proceeds at a potential rate (immediate evapotranspiration reaches PET in the model), changes in soil moisture are governed by precipitation anomalies of short duration.

It should be indicated that the evapoclimatonomy model is a diagnostic model, not a prognostic one, and there is only one unique solution to a particular set of climate/soil/vegetation input forcings. It differs from global climate models (GCMs) in the way the model is initialized and integrated. In contrast to most of the GCMs (Delworth and Manabe, 1989), the model runs do not involve several sets of integrations, with prescribed seasonal cycles of albedo and soil moisture. If the model were run starting with completely dry or saturated soils, it would take a longer time to reach a climatic equilibrium.

4.2. Model runs

The model was run for subsites representing particular vegetation types within the supersites. Subsites selected for model simulations were those for which daily rainfall data were available from the EPSAT-Niger network (Prince et al., 1994; Wallace et al., 1994): the millet fields in the Central East and Central West supersites and the millet and bush fallow subsites in the Southern supersite. For each of these four subsites, the model calculated water balance parameters, including soil moisture. Model output was compared with field observations, as available.

Solar radiation at the surface, potential evapotranspiration, rainfall, NDVI, surface albedo and various vegetation parameters were obtained from the HAPEX-Sahel

Information System (Table 1) for use as model input. Daily climatic information (precipitation and incident and reflected solar radiation) were available for all three supersites. In cases where these data were unavailable at the subsite used for model runs, the data for a neighboring site were utilized. Surface albedo and NDVI were available for each vegetation type in each supersite. PET measurements were available only for the Central East supersite and were assumed representative of all sites.

The IOP extended from August 20 (Julian Day 232) to October 12 1992 (Julian Day 285), a period of 54 days. With the exception of rainfall, input data for the period prior to the IOP were based on climatological values, as utilized in the monthly model (Marengo et al., 1996). Commencing with the IOP, local input data as measured during the experiment were used as model input. Rainfall data were available for model runs for all subsites, beginning in January, 1992

4.3. Analysis of model error

Observations of soil moisture, evapotranspiration, latent heat, and transpiration were variously available for validation of the model. Soil moisture was available for the millet field in Central East supersite and the millet field and bush fallow in the Southern supersite. Evapotranspiration and/or latent heat were available for the bush fallow of the Southern supersite.

In validating GCM results via comparison with observations (Druyan et al., 1995), the root mean square (RMS) method is widely used. In this case, the RMS of the differences between model calculations and observations is derived. In view of the small number of observations, an alternative method is utilized here to analyze model error. The chi-squared test (Spiegel, 1990) is used here to assess the significance of the differences

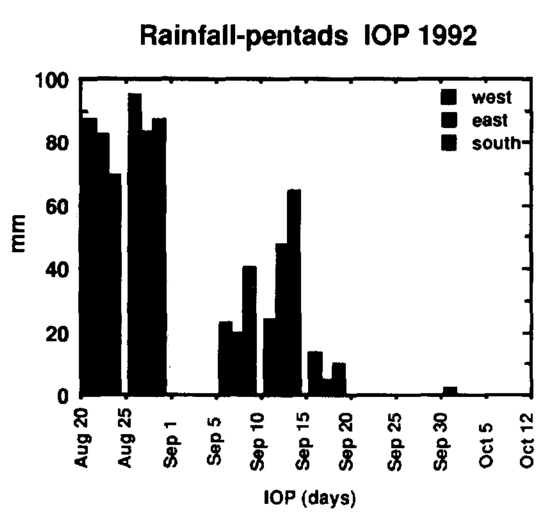

Fig. 2. Rainfall during the intensive observational period (IOP) August 20–October 12 1992, for the Central East, Central West, and Southern supersites of HAPEX-Sahel. Rainfall is accumulated in periods of 5 days (pentads) in mm.

between observed and expected (i.e. modeled) values for measurements made during the IOP.

5. Climatic conditions during the IOP

Climatic conditions in the HAPEX-Sahel area are fully described in Sivakumar (1987), Lebel et al. (1992), Prince et al. (1994), and Goutorbe et al. (1994). Fig. 2 shows the accumulated rainfall in pentads during the IOP for the three supersites. All three supersites show the intense rains during the periods August 21 to 30 and September 11 and 14. After September 20 almost no rain fell in any of the three supersites. The total rainfall at the Southern supersite during the IOP was 193 mm for the millet field and 267 mm for bush fallow; 187 mm fell during the IOP at the millet field in the Central East supersite.

The meteorological conditions during the IOP at the Central East supersite are shown in Fig. 3. At the beginning of the IOP, the frequency of rains at the Eastern supersite increased, indicating that the soil remained wetter for longer periods, with more energy expended in the form of latent heat than in sensible heat, thus, lowering the maximum air temperature (Fig. 3(A)), as compared with later in the season when rainfall events were widely separated. Air temperature increased with increasing solar radiation (Fig. 3(B)) and possibly reduced cloud cover after September 15. Daytime temperatures reached a

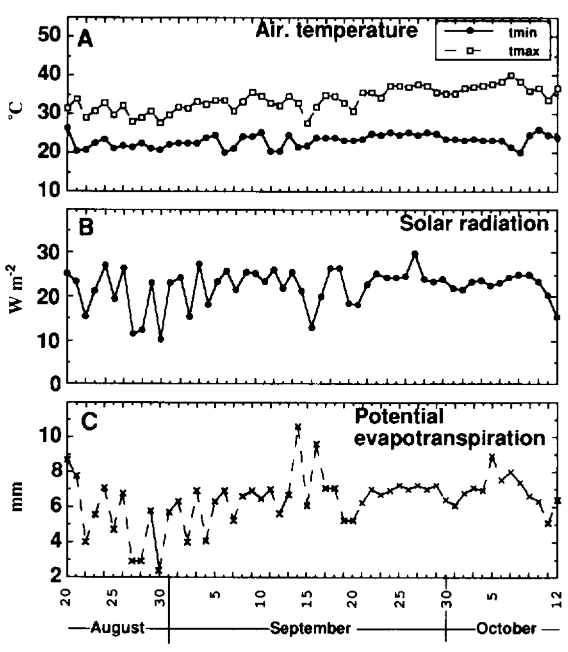

Fig. 3. Climatic conditions during the IOP for the Central Eastern site, based on HAPEX-Sahel site-observations. (A) Maximum and minimum temperature (°C); (B) global solar radiation at surface (MJ m^{-2}); (C) potential evapotranspiration (mm).

maximum of approximately 43°C after the rains ended during October, but during the rainy season averaged 30°C. Minimum temperatures (Fig. 3(A)) were on average about 20°C.

During the period without rain after mid-September, potential evapotranspiration was considerably higher than at the beginning of the IOP (Fig. 3(C)). This was due to greater availability of solar radiation (Fig. 3(B)) and sensible heat (shown by higher air temperatures). This shift from latent to sensible heat transfer during the IOP is also reflected in large values of the Bowen ratio as shown in Fig. 10 in Prince et al. (1994).

6. Model results of water balance in the HAPEX-Sahel supersites

A comparison of observed and model-calculated soil moisture (Fig. 4(a)–(d)) demonstrates excellent agreement with respect to trends in soil moisture and timing of peaks and minima, but significant disagreement in magnitude. In all cases, soil moisture generally peaks within a day or two of the rainfall.

Modeled soil moisture was generally about 15 to 30% above observed, with better agreement at the Central East supersite than at the Southern supersite. Observed soil moisture peaked at about 100 to 130 mm at the three sites with available soil moisture data. In contrast, the model produced peaks as high as 140 to 170 mm. Low values

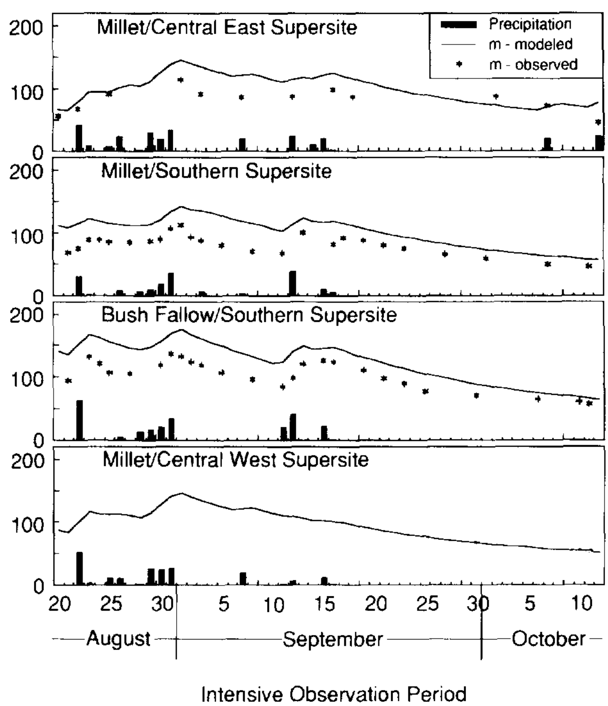

Fig. 4. Observed and modeled soil moisture (mm) for HAPEX-Sahel supersites during the IOP. (a) Millet, Central East supersite; (b) millet, Southern supersite; (c) bush fallow, Southern supersite; (d) millet, Central West (no observations available).

observed at the beginning of the HAPEX IOP were on the order of 60 to 100 mm and values at the end of the IOP were on the order of 50 to 70 mm. The model adequately predicted those at the end of the IOP, producing values on the order of 60 to 80 mm. There was a greater discrepancy between observed and modeled values at the onset of the IOP, with modeled soil moisture being about 70 mm for millet at the Central East supersite and 110 to 160 mm at the Southern supersite.

Fig. 5 shows scatter plots of observed vs modeled soil moisture. Because the model effectively captures the diurnal variations, correlations are quite high, ranging from 0.79 for the Central East millet field to 0.95 for the bush fallow at the Southern supersite. However, the magnitudes differ considerably and the chi-squared test indicates that these differences are significant. This, together with the high correlations between calculated and observed soil moisture, suggests a systematic overestimation of soil moisture by the model.

Fig. 6(a)–(d) shows modeled total evapotranspiration and total runoff. Peaks in total evapotranspiration followed those of rainfall. A reduction in total evapotranspiration as the soil dried out and plants reduced their levels of evapotranspiration is clearly indicated during the dry-out period after the end of September at all four subsites. In general, evapotranspiration exceeded runoff except during the most extreme rain event (compare Figs 4, and 6).

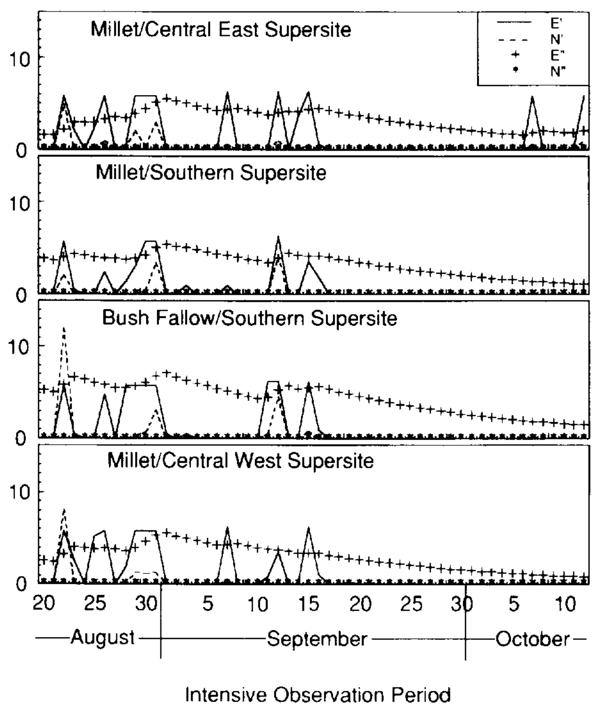

Fig. 5. Scatter plots of observed vs. modeled soil moisture (mm) for fields in the Central East and Southern supersites. The dashed line indicates expected values in the case of perfect agreement between observed and modeled values. Correlations between observed and modeled values (r) are indicated.

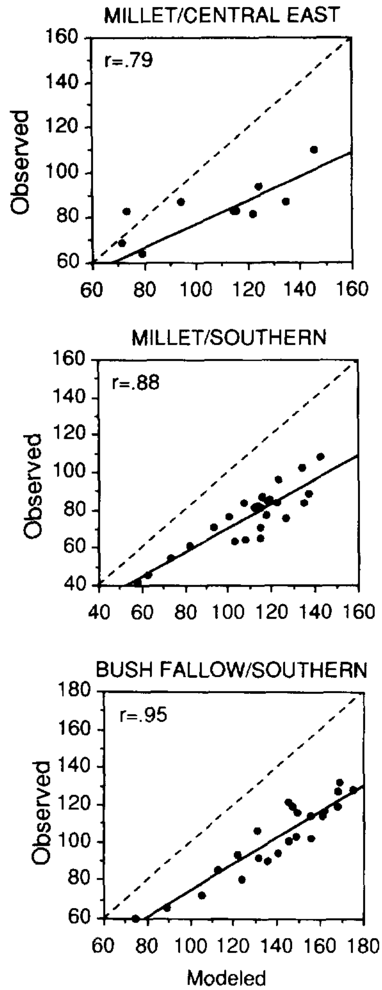

Fig. 6. Total and delayed evapotranspiration and total runoff (mm), as modeled for HAPEX-Sahel supersites during the IOP. (a) Millet, Central East supersite; (b) millet, Southern supersite; (c) bush fallow, Southern supersite; (d) millet Central West.

Fig. 7 shows the partitioning of immediate and delayed processes, as calculated by the model. Immediate evapotranspiration is primarily the result of ground evaporation from the soil surface and evaporation from the water collected in surface depressions, while delayed evapotranspiration is mostly the result of transpiration by plants, with some ground evaporation from soil moisture. Immediate runoff is essentially storm runoff and includes precipitation which does not become available for soil moisture storage, while delayed runoff is essentially gravity drainage from lower soil layers. For the HAPEX-Sahel supersites, the model indicates that immediate exceeded delayed evapotranspiration only during periods when precipitation was high but had not yet infiltrated into the soil and was thus unavailable to plants. The delayed component was

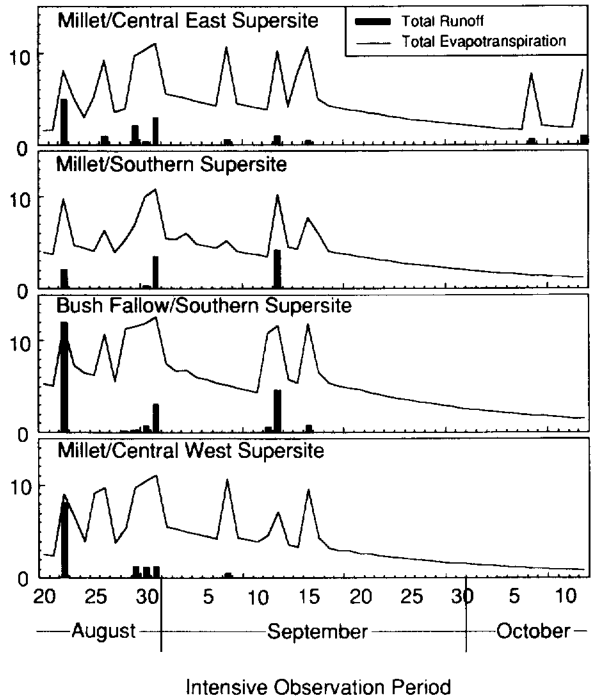

Fig. 7. Immediate and delayed evapotranspiration and runoff (mm), as modeled for HAPEX-Sahel supersites during the IOP. (a) Millet, Central East supersite; (b) millet, Southern supersite; (c) bush fallow, Southern supersite; (d) millet Central West.

generally 3 to 6 mm day^{-1}, roughly in agreement with measurements of transpiration presented by Wallace et al. (1994). The model also indicated that nearly all the runoff occurring during the HAPEX-Sahel experiment was due to storm rain and so delayed runoff was almost negligible, which is also consistent with the region's hydrology (Entekhabi, 1984). It is also consistent with the infiltration capacity for these soils, which determines the threshold for delayed runoff. It is on the order of 150 mm month^{-1}, a value rarely exceeded in the model calculations of soil moisture.

Fig. 8 compares observed and modeled evapotranspiration for the Central West millet field. The agreement is good for both variability and magnitude. The correlation between observed and modeled values is 0.86. The chi-squared test indicates that there is no significant difference between the observed and modeled evapotranspiration, suggesting acceptable differences in the magnitude of the values.

7. Discussion

The results of our investigation suggest that the evapoclimatonomy model adequately simulated hydrologic processes at the daily scale in some cases. However, shortcomings

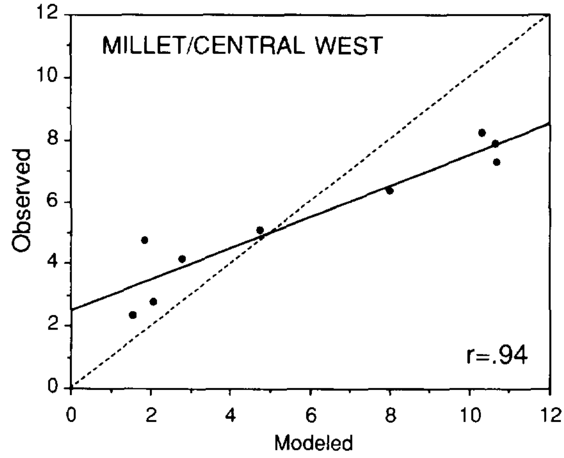

Fig. 8. Scatter plot of observed vs. modeled evapotranspiration (mm) for the millet field at the Central West supersite. The dashed line indicates expected values in the case of perfect agreement between observed and modeled values. Correlation between observed and modeled values (r) is indicated.

were apparent, particularly in the overestimation of soil moisture. In general, the results were less promising than those for the monthly scale (Marengo et al., 1996); in that case, differences between observed and calculated values were on the order of 8%. Greater discrepancies at daily scales are to be expected, as runoff, precipitation and soil moisture

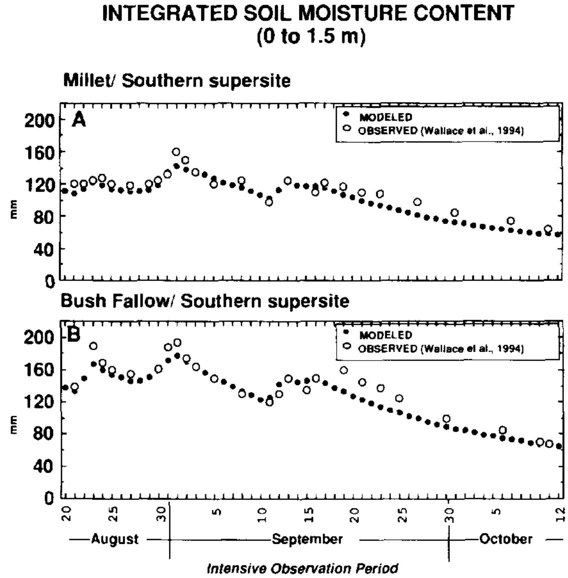

Fig. 9. Modeled soil moisture storage (mm) to 1.0 m depth, and to 1.5 m depth as derived by Wallace et al. (1994) at the Southern supersite during the IOP. Data for millet (A) and bush fallow (B) are means of seven profiles (this work) and ten profiles (Wallace et al., 1994).

all exhibit greater variability at shorter time and space scales. Nevertheless, the degree of overestimation of soil moisture is considerable.

The overestimation of soil moisture may be a manifestation of inadequacies in the formulation of key model parameters, such as residence time or hydraulic conductivity, which control the rate of soil moisture depletion, and/or infiltration capacity, which controls the rate of generation of soil moisture. It is noteworthy that the model is highly sensitive to clay content, which strongly influences both infiltration capacity and hydraulic conductivity. Furthermore, clay contents of 5% (as in the HAPEX sites) are at the limit of the validity of the parameterizations of infiltration capacity and water holding capacity, which were empirical fits to observed data (Lare, 1992).

An additional factor which could be linked to the overestimation of soil moisture is the initial assumption that soil moisture exchange processes on a daily scale are largely confined to the 1.0-m layer. A look at daily soil moisture variability at the Southern supersite indicated that deeper layers showed considerable daily variability, down to about 1.50 m. Therefore the model-calculated soil moisture would be more appropriately compared with observed soil moisture integrated to at least 1.50 m at this site.

The observed integrated soil moisture for the 1.50-m layer is shown in Fig. 9 for both millet and bush fallow at the Southern supersite. These values are about 30–50% higher than those for the 1.0-m layer (Fig. 9). A comparison of model-calculated soil moisture for both the millet and guiera (Fig. 4(b) and (c)) showed excellent agreement with these observations (Fig. 9(A) and (B)). In both cases correlations between modeled and observed soil moisture were 0.95.

8. Summary and conclusions

The evapoclimatonomy model revised for simulating hydrologic processes on daily time scales was applied to four fields at two HAPEX-Sahel supersites. The model showed excellent agreement with respect to trends and variability but overestimated the magnitude of soil moisture in three of the four cases. There was also good agreement between observed and modeled evapotranspiration.

An analysis of results suggested several possible sources of error, indicating areas in which the model can be improved. These include the physical parameterization of evaporative processes, the assumptions concerning the depth of soil moisture exchange processes, and the relationship between hydraulic conductivity and soil texture. The latter is particularly important for applications of the model to semi-arid regions in Africa with sandy soils, because the empirical parameterization used in the model gives unrealistic values of soil variables when clay content is extremely low.

The systematic overestimation of soil moisture is most likely due to the assumption that on a daily scale the soil moisture exchange via runoff, infiltration and evapotranspiration is confined to the first meter of soil. A look at the soil moisture profile clearly showed that to be in error and the model estimate is value only for the entire depth over which these exchanges take place. This underscores the necessity of having some prior knowledge of local soil conditions before the model can be successfully applied.

Acknowledgements

We would like to thank Drs. T. Lebel and B. Monteny, Principal Investigators of the HAPEX-Sahel projects whose hydrological and climatological data were used in this paper. We also want to extend our thanks to the EPSAT-Niger and the AGRHYMET Center (Niamey) research teams, and to the staff of the HAPEX-Sahel Information System (HSIS) in Toulouse, France. In particular, we wish to thank Shelly Thawley from the Department of Geography at the University of Maryland for providing us with access to the HAPEX-Sahel data base, and Jeeyoung Kim for his help in the development of the model. Support for the project was provided by NASA grants NAGW-3101 and NAG-5-1587 to Florida State University. We would like to thank J.D. Cooper for soil moisture data.

References

Brakensieck, E.L. and Rawls, W.J., 1983. Agriculture management effects on soil water processes. Part II. Green and Ampt parameters for crusting soils. Trans. Am. Soc. Agric. Eng., 26: 1753–1757.

Brubaker, K., Entekhabi, D. and Eagleson, P., 1993. Estimation of continental precipitation recycling. J. Clim., 6: 1077–1089.

Delworth, T. and Manabe, S., 1989. The influence of soil wetness on near-surface atmospheric variability. J. Clim., 2: 1447–1462.

Dorman, J.L. and Sellers, P.J., 1989. A global climatology of albedo, roughness length, and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere Model (SiB). J. Appl. Meteor., 28: 833–855.

Druyan, L., Lo, W.K., Shah, K., Marengo, J.A. and Russell, G., 1995. Impacts of model improvements on GCM sensitivity to SST forcing. Int. J. Climatol., 15: 1061–1086.

Entekhabi, D., 1984. Spectral analysis and stochastic modelling of streamflow using the Fourier series: the case of the Niger River. Ms. Arts thesis, Department of Environmental Affairs, Clark University, Worcester, MA, 126 pp. (Available from Department of Environmental Affairs, Clark University, Worcester, MA.).

Entekhabi, D., Rodriguez-Iturbe, I. and Bras, R., 1992. Variability in large-scale water balance with a land surface interaction. J. Clim., 5: 798–813.

FAO, 1984. Agroclimatological Data. Vol. I and III, Food and Agricultural Organization, Rome.

FAO/UNESCO, 1977. Soil Map of the World. Vol VI, Africa. UNESCO, Paris, 218 pp.

Farrar, T.J., Nicholson, S.E. and Lare, A.R., 1994. The influence of soil type on the relationships between NDVI, rainfall and soil moisture in semi-arid Botswana. Part II. Relationship to soil moisture. Remote Sens. Environ., 50: 121–130.

Gardner, C.M., Bell, J.P., Cooper, J.D., Hodnett, M.G. and Gardner, N., 1991. Soil water content. In: K.A. Smith and C.E. Mullins (Editors), Soil Analysis: Physical Methods. New York, pp. 1–73.

Goutorbe, J.-P., Lebel, T., Tinga, A., Bessemoulin, P., Brower, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P., Kerr, Y.H., Monteny, B., Prince, S., Said, F., Sellers, P.J. and Wallace, J.S., 1994. HAPEX-Sahel: a large scale observational study of land–atmosphere interaction in the semiarid-tropics. Ann. Geophys., 12: 53–64.

Kabat, P., Gash, J.H.C., Stricker, J., Cuenca, R. and Prince, S., 1993. Spatial and temporal variability of surface fluxes as related to soil moisture and vegetation changes. In: Proceedings American Geophysical Union Fall Meeting, 5–10 December 1993, San Francisco, CA. 252 pp.

Kerr, Y.H., Lagouarde, J. and Imbernon, J., 1992. Accurate land surface temperature retrieval for AVHRR data with use of an improved split window algorithm. Rem. Sens. Environ., 41: 197–209.

Kerr, Y., Valero, T. and Wagner, S., 1993. HAPEX-Sahel Information System CD-ROM 1 and 2. AVHRR92. (Available from HAPEX-Sahel Information System, LERTS, 18 Avenue E. Bolin, 31055 Toulouse CEDEX, France.).

Lare, A.R., 1992. An investigation into land-surface feedback and the African drought using climatonomy modeling. Ph.D. dissertation, Department of Meteorology, Florida State University, 333 pp. (Available from Department of Meteorology, Florida State University, Tallahassee, FL.).

Lare, A.R. and Nicholson, S.E., 1990. A climatonomic description of the surface energy balance in the Central Sahel. Part I: Shortwave radiation. J. Appl. Meteor., 29: 123–137.

Lare, A.R. and Nicholson, S.E., 1994. Contrasting conditions of surface water balance in wet and dry years as a possible land surface–atmosphere feedback mechanism in the West African Sahel. J. Clim., 7: 653–668.

Lebel, T.H. and LeBarbe, L., 1997. Rainfall climatology in the Central Sahel during the years 1950–1990. J. Hydrol., this issue.

Lebel, T., Sauvageout, H., Hoepffner, M., Desbois, M., Guillot, B. and Hubert, P., 1992. Rainfall estimation in the Sahel: the EPSAT-Niger experiment. Hydrol. Sci. J., 37: 201–215.

Lebel, T.H., Taupin, J.D. and Greard, M., 1995b. Rainfall monitoring: the EPSAT-Niger set-up and its use for HAPEX-Sahel. In: T. Lebel (Editor), Hydrologie et Meteorologie de Meso-Echelle dans HAPEX-Sahel: Dispositif de Mesures au Sol et Premier Results. ORSTOM, pp. 43–82.

Lebel, T.H., Taupin, J.D. and LeBarbe, 1997. Space–time fluctuations of rainfall during HAPEX-Sahel. J. Hydrol., this issue.

Lettau, H.H., 1969. Evapotranspiration climatonomy. I. A new approach to numerical prediction of monthly evapotranspiration, runoff and soil moisture storage. Mon. Wea. Rev., 97: 691–699.

Lettau, H.H. and Baradas, M.W., 1973. Evapotranspiration climatonomy II: refinement of parameterizations exemplified by application to the Mabacan River watershed. Mon. Wea. Rev., 101: 636–649.

Marengo, J.A., Nicholson, S.E. and Lare, A.R., 1996. Application of evapoclimatonomy to monthly surface water balance calculations at the HAPEX-Sahel supersites. J. Appl. Meteor., 35: 562–573.

Mintz, Y. and Serafini, Y., 1984. Global fields of monthly normal soil moisture, as derived from observed precipitation and an estimated potential evapotranspiration. Final scientific report under NASA Grant No. NAS 5-26, part V, Department of Meteorology, University of Maryland.

Monteny, B.A., 1993. HAPEX-Sahel 1992, Campagne de mesures, Supersite Central Est. ORSTOM, Montpellier, 230 pp.

Nicholson, S.E., 1986. African drought: as example of the influence of land surface properties on climate? In: Proceedings Conference on Parameterization of Land-Surface Characteristics, Use of Satellite Data, and First Results of the ISLSCP. European Space Agency, Paris, France, pp. 405–410.

Nicholson, S.E., 1989. African drought: characteristics, causal theories and global teleconnections. In: A. Berger, R.E. Dickinson and J.W. Kidson (Editors), Understanding Climate Change. Am. Geophys. Union, Washington, DC, pp. 79–100.

Nicholson, S.E. and Lare, A.R., 1990. A climatonomic description of the surface energy balance in Central Sahel. Part II: The evapoclimatonomy submodel. J. Appl. Met., 29: 138–146.

Nicholson, S.E., Lare, A.R., Marengo, J.A. and Santos, P., 1996. A revised version of Lettau's evapoclimatonomy model. J. Appl. Meteor., 35: 549–561.

Prince, S., Kerr, Y.H., Goutorbe, J.-P., Lebel, T., Tinga, A., Bessemoulin, P., Brower, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P., Monteny, B., Said, F., Sellers, P. and Wallace, J., 1994. Geographic, biologic and remote sensing aspects of the Hydrologic-Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel). Int. J. Remote Sensing, accepted.

Rawls, W.J. and Baumer, O., 1989. Calibration of modified Kozency–Carman saturated hydraulic conductivity equation. ASCE J. Irrig. Drain.

Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.J., 1986. Estimating generalized soil–water characteristics from texture. Soil. Sci. Soc. Am. J., 50: 1031–1036.

Serafini, Y.V. and Sud, Y.C., 1987. The time-scale of the soil hydrology using a simple water budget model. J. Climatol., 7: 585–591.

Sivakumar, M.V.K., 1987. Climate of Niamey. Progress Report – 1. ICRISAT Sahelian Center, Niamey, Niger. International Crops Research Institute for the Semiarid Tropics, 36 pp.

Spiegel, M., 1990. Statistics. Schaum's Outline Series of Mathematics. McGraw-Hill Publishing Company, New York, 504 pp.

Tucker, C.J. and Sellers, P.J., 1986. Satellite remote sensing of primary production. Int. J. Remote Sensing, 7: 1395–1416.

Tucker, C.J., Holben, B., Elgin, J. and Murtrey, J.M., 1981. Remote sensing of total dry-matter accumulation in winter wheat. Remote Sensing Environ., 11: 171–189.

Tucker, C.J., Vanpraet, C., Boerwinkel, E. and Gaston, A., 1983. Satellite remote sensing of total dry matter production in the Senegalese Sahel. Remote Sensing Environ., 13: 461–474.

Tucker, C.J., Vanpraet, C.L., Sharman, M.J. and Van Ittersum, G., 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–84. Remote Sensing Environ., 17: 233–249.

Wallace, J., Brower, J., Allen, S.J., Banthorpe, D., Blyth, E.M., Blyth, K., Bromley, J., Buerkert, A.C., Cantwell, M., Cooper, J.D., Cropley, F.D., Culf, A.D., Dolman, A.J., Dudgale, G., Gash, J.H., Gaze, S.R., Harding, R.J., Harrison, R.G., Holwill, C.J., Jarvis, P.G., Levy, P.E., Lloyd, C.R., Malhi, Y.S., Massheder, J.M., Moncrieff, J.B., Pearson, D., Settle, J.J., Sewell, I.J., Sivakumar, M.V.K., Sudlow, J.D., Taylor, C.M. and Wilson, A.K., 1994. HAPEX-Sahel Southern Supersite Report: An Overview of the Site and the Experimental Programme During the Intensive Observation Period in 1992. Institute of Hydrology, Wallingford, UK, 55 pp.

Warrilow, D., 1986. The sensitivity of UK meteorological office atmospheric general circulation model to recent changes to the parameterization of hydrology. In: Proc. ISLSCP Conference, 2–6 December 1985, Rome, Italy. ESA SP-248, pp. 143–149.

Webb, R.S., Rosenzweig, C.E. and Levine, E.R., 1991. A global data set of soil particle size properties. NASA Tech. Memo. 4286, 33 pp.

Xue, Y. and Shukla, J., 1993. The influence of land surface properties on Sahel climate. Part I: desertification. J. Clim., 6: 2232–2245.

Zobler, L., 1986. A world soil file for global climate modeling. NASA Tech. Memo. 87802.